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FINAL SCIENTIFIC REPORT

1 August 1988 - 31 October 1989

Grant: AFOSR No. 88-0252

Principal Investigator: A. V. Balakrishnan  
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## I. ACCOMPLISHMENTS

Reportable progress has been achieved during the period 1 August, 1988 to 31 Oct, 1989 in the following areas of proposed activity.

### 1. Active Control of Large Space Structures

#### Compensator Design

Perhaps the most significant single contribution is the successful solution of the problem of Compensator Design for co-located sensors using continuum models of flexible multibody systems. Since the state in a continuum model is not finite dimensional, an explicit Kalman filter block would be impossible to realize, and hence direct compensator design is the only possible alternative. We have been able to achieve this by stochastic optimization theory -- by incorporating an appropriate state-noise model, and treating it as a "Stochastic Regulator" problem, in which the boundary rates (mean square average) are minimized subject to a soft constraint on the control effort. Such a problem has been treated in the Principal Investigator's monograph [1]. The theory in [1] requires that the system be exponentially stabilizable -- which is not possible since the control operator is compact. However if the Large Space Structure system can be shown to be strongly stabilizable, the theory developed in [1] goes through. But more importantly it turns out that the infinite dimensional steady state Riccati equations can be solved in closed form -- a major contribution in itself since such cases are extremely rare. In particular the solution can be useful for testing efficiency of the many numerical computing schemes proposed for solving such equations. In any event the closed form solution makes possible explicit calculation of the achievable minimal boundary

rates for given control effort -- see [2], [3] -- (the theoretical aspects are emphasized in [2]). In particular the performance indices show the role played by the structure as contrasted with that of the controller -- a typical case of controls-structures interaction. In addition the performance of the compensator is evaluated when in the "truth model" there is in fact no actuator noise. The nontrivial part in the theory here is to show that a steady state exists -- in particular this needs the Principal Investigator's white noise theory [1] since the steady state covariance operators are no longer nuclear and hence the Wiener process formalism would not apply. In other words this problem completely vindicates the whole gamut of theory -- Stochastic Control in Hilbert Space -- pioneered by the Principal Investigator. It should also be noted that the results obtained make possible the solution of the optimal selection problem for placement of proof-mass actuators.

#### Damping Models: Linear Case

One of the uncertainties in Large Space Structures involves the nature and extent of the inherent damping. Even if we assume that the damping is linear, the exact characterization of the damping models is still an open question. There is considerable evidence -- and in fact it is widely accepted -- that the damping must be proportional to the mode frequency: "proportional damping." If we assume strict proportionality, then the damping operator has to be the square root (essentially) of the stiffness operator as shown in [4]. The problem of calculating the square root in each specific case is nontrivial. An explicit calculation of the square root for the case of beam torsion is presented in [5]. The square root operator is nonlocal and includes terms on the boundary. In particular for the "clamped" beam the square root is shown to have the form of

a "finite limit" Hilbert transform. The square root operator for beam bending with end bodies is developed in [6], and is shown to be nonlocal as well as including boundary terms. We show that if strict proportionality is relaxed to "asymptotic" proportionality, the corresponding damping operator is indeed local although still involving boundary terms.

#### Damping Models: Nonlinear Case

Experimental results on single-mode free response of trusses exhibit significant nonlinear damping at high amplitudes. To account for this observed behavior a class of nonlinear damping models have been developed. The first results are presented in [7], where in particular the Krylov-Bogoliubov averaging technique provides a remarkably good approximation to the solution of the corresponding nonlinear differential equations for the range of damping ratios of interest. Using this technique it is shown that there is one universal model -- the "energy" model which will yield the same free response for appropriate parameter choice as all of the known nonlinear models: Coulomb friction, etc. This in turn raises the question whether forced response -- in particular response to random white noise input -- could help resolve the ambiguity. Early results along these lines are presented in [8]. Finally several nonlinear damping models for general distributed parameter systems -- beam models of flexible multibody systems -- are developed in [9].

## 2. Random Fields

The dissertation by R. Leland [10] continued the approach initiated in [11] for coherent (laser) beam propagation in atmospheric turbulence in which the main point of departure is modelling the Markov approximation as white noise rather than as Wiener process-plus-adhoc Stratonovich correction. In particular

it is shown that band-width expansion yields the white noise model in the limit. In addition a digital simulation of the laser propagation in strong turbulence was carried out in verification of the theory. This work has been accepted for inclusion as a monograph in the Springer-Verlag Lecture Notes Series in Control and Information [12].

#### References

1. Balakrishnan, A.V. *Applied Functional Analysis*. New York: Springer-Verlag, 1981.
2. Balakrishnan, A.V. "Feedback Control for Stabilization of Flexible Multi-body Structures." In: *Proceedings of the Conference on Differential Equations Theory and Applications in Stability and Control, Colorado Springs, June 1989*.
3. Balakrishnan, A.V. "Compensator Design for Stability Enhancement with Co-located Controllers." In: *Proceedings of the IFAC Conference on Control of Distributed Parameter Systems, Perpignan, France, June 1989*.
4. Balakrishnan, A.V. "Control of Flexible Flight Structures." In: *Mathematique et applications*. Paris: Gauthier-Villars, 1988.
5. Balakrishnan, A.V. "Damping Operators in Continuum Models of Flexible Structures: Explicit Models for Proportional Damping in Beam Torsion." To be published in *The Journal of Differential and Integral Equations*, 1990.
6. Balakrishnan, A.V. "Damping Operators in Continuum Models of Flexible Structures: Explicit Models for Proportional Damping in Beam Bending with End Bodies. To be published in *Journal of Applied Mathematics and Optimization*, 1990.

7. Balakrishnan, A.V. "A Theory of Nonlinear Damping in Flexible Structures."  
In: *Proceedings of the Workshop on Stabilization of Flexible Structures, Montpellier, France, December 1987.* New York: Optimization Software Publications, 1987.
8. Zhang, Weijian. "Nonlinear Damping Model: Response to Random Excitation."  
In: *Proceedings of the 5th Annual SCOLE Workshop, November 1988.* Ed. L.W. Taylor.
9. Taylor, L.W. and A.V. Balakrishnan. "Distributed Parameter Nonlinear Damping Models for Flight Structures." In: *Proceedings of the Conference, "Damping '89."* Ed. Lynn Rogers. Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, 1989.
10. Leland, R. "Stochastic Models for Laser Propagation in Atmospheric Turbulence."  
Ph.D. dissertation. UCLA, 1989.
11. Balakrishnan, A.V. "A Random Schroedinger Equation: White Noise Model."  
*The Journal of Differential and Integral Equations*, Vol. 1, No. 1 (January 1988), pp. 49-70.
12. Leland, R. "Stochastic Models for Laser Propagation in Atmospheric Turbulence." Lecture Notes Series on Control and Information Sciences, Vol. 133. New York, Berlin, Heidelberg: Springer-Verlag, 1989.



## II. LIST OF PUBLICATIONS

### Papers

1. Balakrishnan, A.V. "Feedback Control for Stabilization of Flexible Multibody Structures." In: *Proceedings of the Conference on Differential Equations Theory and Applications in Stability and Control, Colorado Springs, June 1989.*
2. Balakrishnan, A.V. "Compensator Design for Stability Enhancement with Co-located Controllers." In: *Proceedings of the IFAC Conference on Control of Distributed Parameter Systems, Perpignan, France, June 1989.*
3. Balakrishnan, A.V. "Damping Operators in Continuum Models of Flexible Structures: Explicit Models for Proportional Damping in Beam Torsion." To be published in *The Journal of Differential and Integral Equations*, 1990.
4. Balakrishnan, A.V. "Damping Operators in Continuum Models of Flexible Structures: Explicit Models for Proportional Damping in Beam Bending with End Bodies." To be published in *Journal of Applied Mathematics and Optimization*, 1990.
5. Balakrishnan, A.V. "A Theory of Nonlinear Damping in Flexible Structures." In: *Proceedings of the Workshop on Stabilization of Flexible Structures, Montpellier, France, December 1987.* New York: Optimization Software Publications, 1988.
6. Zhang, Weijian. "Nonlinear Damping Model: Response to Random Excitation." In: *Proceedings of the 5th Annual SCOLE Workshop, November 1988.* Ed. L. W. Taylor.
7. Taylor, L.W. and A.V. Balakrishnan. "Distributed Parameter Nonlinear Damping Models for Flight Structures." In: *Proceedings of the Conference, "Damping*

'89." Ed. Lynn Rogers. Flight Dynamics Laboratory, Air Force Wright  
Aeronautical Laboratories, 1989.

Dissertations

Leland, R. "Stochastic Models for Laser Propagation in Atmospheric Turbulence."  
Ph.D. dissertation. UCLA, 1989. Monograph based on thesis published in the  
Lecture Notes Series on Control and Information Sciences, Vol. 133. New York,  
Berlin, Heidelberg: Springer-Verlag, 1989.

III. ACTIVITIES OF PRINCIPAL INVESTIGATOR 1 AUGUST 1988 - 31 OCT 1989

1. Chairman, International Program Committee, Workshop on Stabilization of Flexible Structures, Montpellier, France, 23-26 January 1989.
2. Member, International Program Committee, IFIP Conference on System Modelling and Optimziation, Leipzig, East Germany, 3-7 July 1989.
3. Invited Plenary Speaker, IFAC Conference on Control of Distributed Parameter Systems, Perpignan, France, 23-29 June 1989.
4. Invited Plenary Speaker, Conference on Differential Equations Theory and Applications in Stability and Control, Colorado Springs, June 1989.
5. Member, International Program Committee, Com-Con 1988: Advances in Communication and Control Systems, Baton Rouge, Louisiana, 19-21 October 1988.
6. Member, International Program Committee, 6th IFIP Conference on Stochastic Systems and Optimization, Warsaw, Poland, 12-18 September 1988.